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Very high power THz radiation at Jefferson Lab

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Abstract

We report the production of high power (20 W average, ∼1 MW peak) broadband THz light based on coherent emission from relativistic electrons. We describe the source, presenting theoretical calculations and their experimental verification. For clarity we compare this source with that based on ultrafast laser techniques, and in fact the radiation has qualities closely analogous to those produced by such sources, namely that it is spatially coherent, and comprises short duration pulses with transform-limited spectral content. In contrast to conventional THz radiation, however, the intensity is many orders of magnitude greater due to the relativistic enhancement.

1. Introduction

The THz source is located at the Free Electron Laser (FEL) Facility at Jefferson Lab. This laboratory operates the first of a new generation of light sources based on a photo-injected energy-recovered (superconducting) linac (ERL) [1]. The present machine has a 48 MeV electron beam and an average current of 5 mA. The electrons are contained in bunches which are extremely short with full-width-half-maximum (FWHM) values that are in the few hundred femtosecond regime. These electron bunches pass a chicane around the optical cavity, and therefore emit synchrotron radiation. When the electron bunch length approaches that of the wavelength of the light being emitted, the entire bunch of up to 130 pC of charge (9×10^8 electrons) radiates coherently [2]. The result is a broadband spectrum whose average brightness is more than five orders of magnitude higher than can be obtained from conventional incoherent synchrotron IR sources, which themselves have a brightness that is three orders of magnitude higher than a 2000 K thermal source.

In order to understand the origin of the many orders of magnitude gain realized in these experiments, we make a comparison with a more conventional (non-relativistic) THz source, see figure 1. It should be noted, however, that this comparison, while conceptually useful, will not stand deep quantitative scrutiny. In both cases a short pulse from a mode-locked laser

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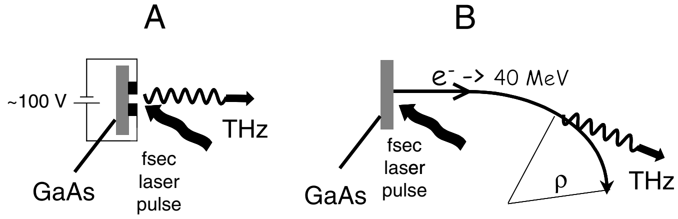

Figure 1. Diagram showing the comparison between a conventional ultrafast laser-driven THz source (A) and the high power source presented here (B).

strikes a GaAs wafer, generating charge carriers. Thus the number of radiating charges is comparable. We can therefore compare the power produced per electron, and use Larmor's formula [3] for the radiated power. In CGS units it takes the form

$$\text{Power} = \frac{2e^2a^2}{3c^3}\gamma^4 \tag{1}$$

where e is the charge, a is the acceleration, c the speed of light and γ is the ratio of the mass of the electron to its rest mass. In case A (the conventional THz emitter), these carriers immediately experience a force from the bias field ($\sim$100 V across a 100 micron gap) of $\sim 10^6$ V m^{-1}, which results in an acceleration of 10^{17} m s^{-2}. The entire process is completed in less than 1 ps, resulting in spectral content up to a few THz. In case B, the same number of charge carriers are brought to a relativistic energy of >10 MeV in a linac, after which a magnetic field bends their path into a circle of radius $\rho = 1$ m resulting in an acceleration $c^2/\rho = 10^{17}$ m s^{-2}, which is the same in case A. An observer of case B also detects a brief pulse of electromagnetic radiation as an electron bunch passes by. But in this case, two factors control the pulse duration; one is the bunch length and the other is the time for the relativistically compressed acceleration field from each electron to sweep past. The latter is given approximately by [3]

$$\delta t = \frac{4\rho}{3\gamma^3 c} \tag{2}$$

and determines the spectral range emitted by each electron. The bunch length determines the spectral range over which the coherent enhancement occurs. For an electron energy of 10 MeV ($\gamma = 21$), and with $\rho = 1$ m, we obtain a δt of about 500 fs, which is comparable to the bunch length itself. The resulting spectral content extends up to about 1 THz, which is the same spectral range in case A. Thus, assuming the same number of electrons, which is true within an order of magnitude, the ratio of the power radiated by the present generation to the conventional THz generation is given by $\gamma^4 = 2 \times 10^5$.

2. Calculations and results

Details of the theory have been presented elsewhere [4], and further details will be presented in an upcoming paper, but in figure 2 we present calculations of the total power emitted by a 500 fs FWHM electron bunch in units of (average) W/cm^{-1} over the range 1–10 000 cm^{-1}, or 1 cm to 1 μm. In the same figure we compare a 2000 K thermal source, and a synchrotron radiation source, namely the National Synchrotron Light Source U4IR facility [5] at Brookhaven National Laboratory. The superiority of the JLab ERL and the onset of the coherent emission are evident. In figure 3, we present the results of our measurements and a comparison with the calculation of figure 2. The spectral content of the emitted THz light was

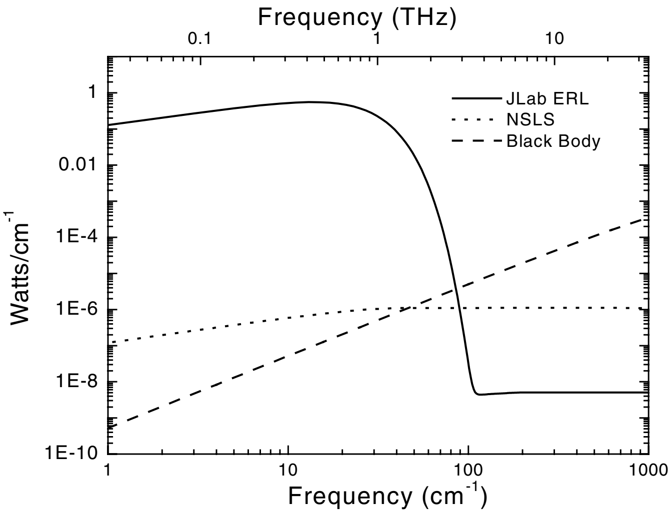

Figure 2. The calculated average THz power from three broadband sources. The blackbody is at 2000 K and the NSLS source is described in [5].

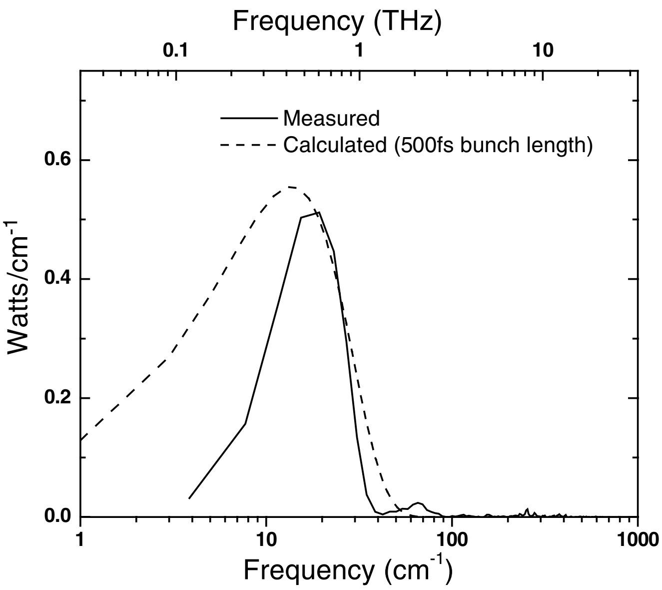

Figure 3. The measured and calculated THz average power at the Jefferson Lab ERL facility.

analysed using a Nicolet 670 rapid-scan Michelson interferometer with a silicon beamsplitter. The light was detected using a 4.2 K Infrared Laboratories bolometer with a 2 mm $\times$ 2 mm boron-doped Si composite element, fed from a 12 mm diameter f/4 Winston cone. It was fitted with a black polyethylene filter to ensure no light above 600 cm^{-1} was detected. Our collection angle was 60 $\times$ 60 mrad and the extraction window was quartz. We were able to determine the absolute power in two ways, one by using a calibrated pyroelectric detector, and the other by comparing our spectra with that from a 1300 K thermal source, by operating the

ERL at a lower repetition rate to enable the large dynamic range to be covered. The data has been scaled on the basis of these absolute power measurements.

The spectral onset of the super-radiant enhancement on the high frequency side is clearly seen, and the onset shape is also seen to match the theoretical predictions closely. Note that there is a severe discrepancy on the lower frequency side due to diffraction effects. This can be understood in the following way. At 10 cm^{-1} and with an $f/17$ beam, the diffraction-limited source size is 17 mm, almost the same as the extraction optics. At 1 cm^{-1}, the diffraction-limited source size would, at 170 mm, be more than three times larger than the vacuum chamber containing the electron beam!

3. Conclusions

We have shown that the short bunches in the new generation of sub-picosecond energy recovery systems yield broadband high brightness far-IR radiation with about $\frac{1}{2}$ $\mathrm{W/cm^{-1}}$ of average power into the diffraction limit. This power is delivered in 500 fsec FWHM pulses every 13.3 ns, so that the peak power is $\sim 2 \times 10^4$ higher than this. Further, we note that the brightness of the ERL source, which is defined as the flux per unit source area per unit solid opening angle is determined by dividing the power by λ^2, since the electron bunch has lateral dimensions that are smaller than the wavelength, and full spatial coherence exists.

Finally we note that the JLab ERL is the first of a new generation of such machines, and in the future it is expected that higher energies and currents will be available, making such sources stronger by many more orders of magnitude. A dedicated THz source based on the principles discussed here may also be made much smaller than the JLab ERL facility.

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